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Los Alamos National Laboratory



SYNTHETIC HYPERSPECTRAL DATA CUBES FOR COMPLEX THERMAL SCENES

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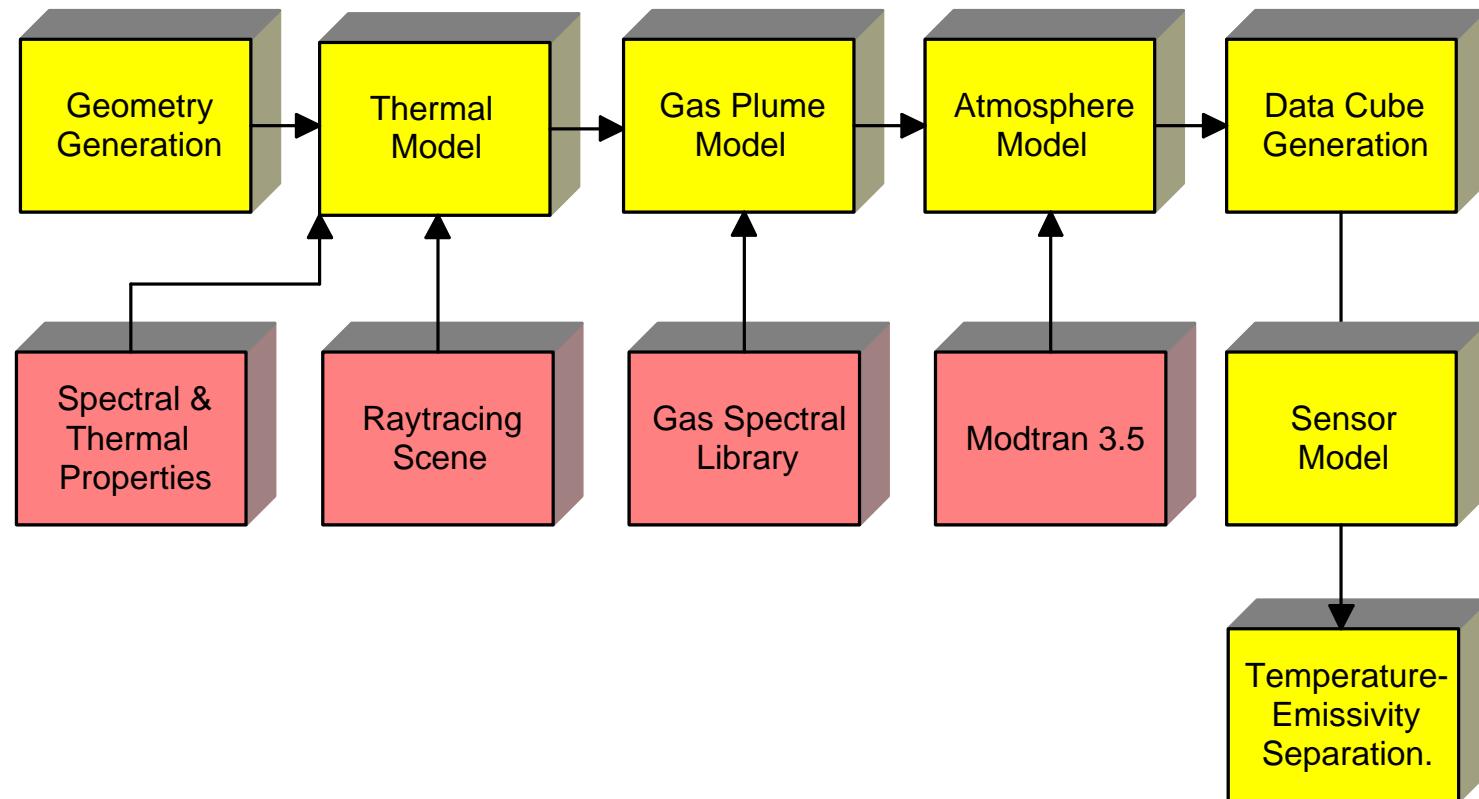
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2. Synthetic Hypercube Generation
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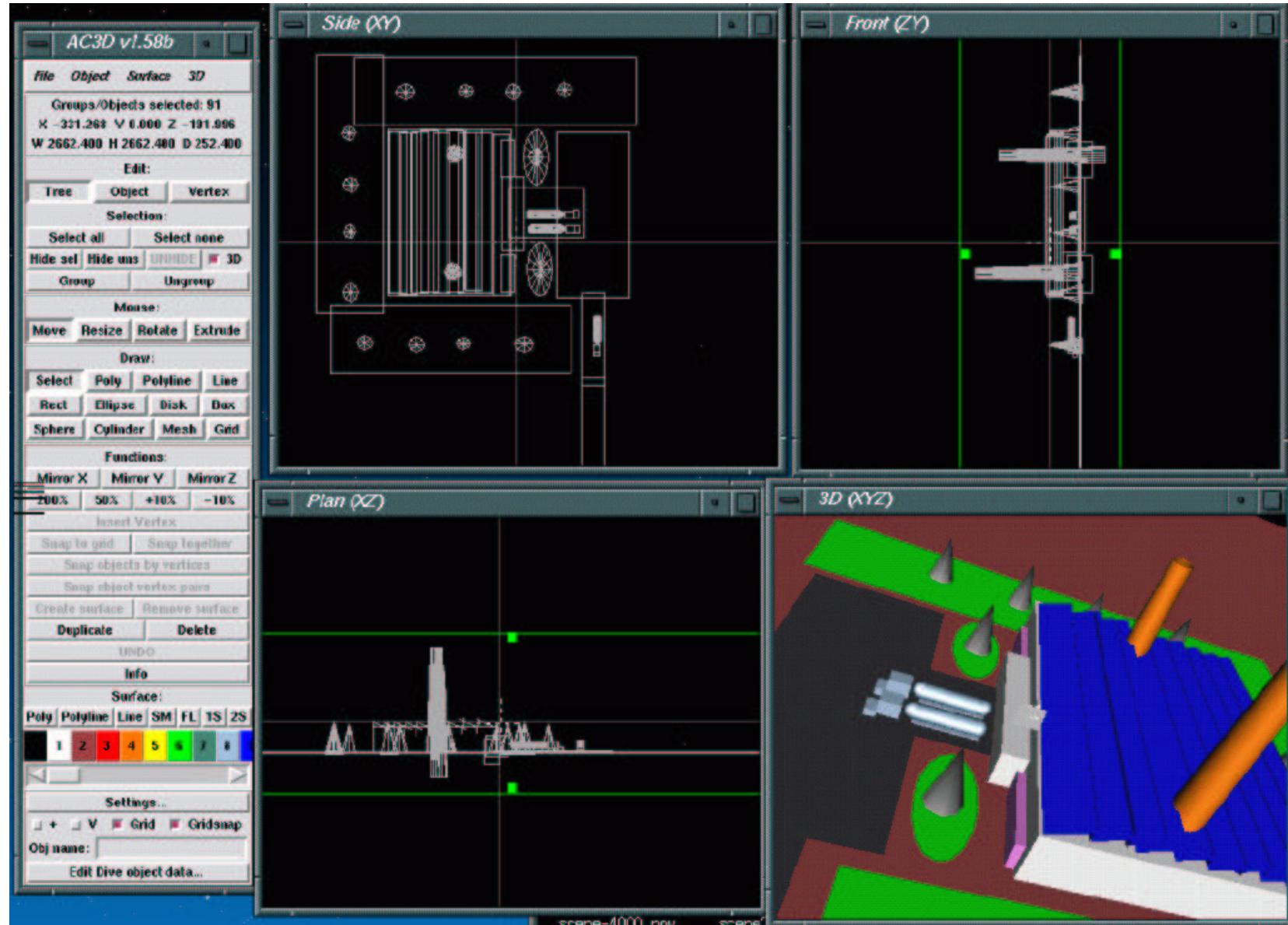
Synthetic Hypercube Generation



GEOMETRY MODEL

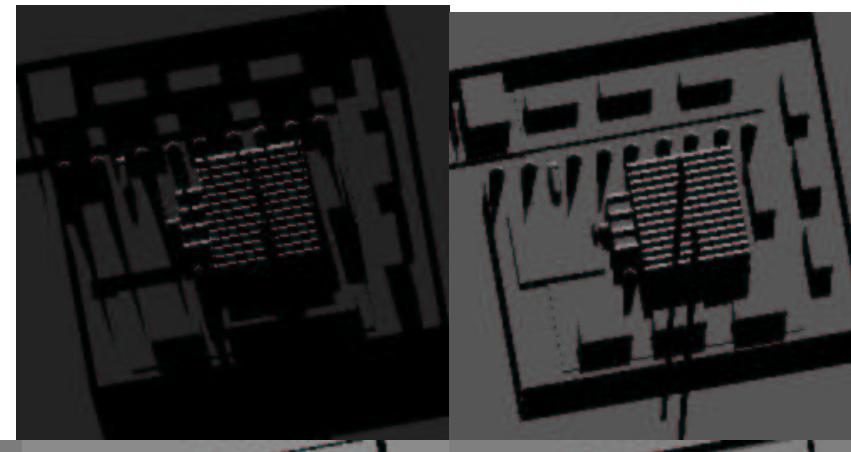
AC3D interface

(www.comp.lancs.ac.uk/computing/users/andy/ac3d.html)



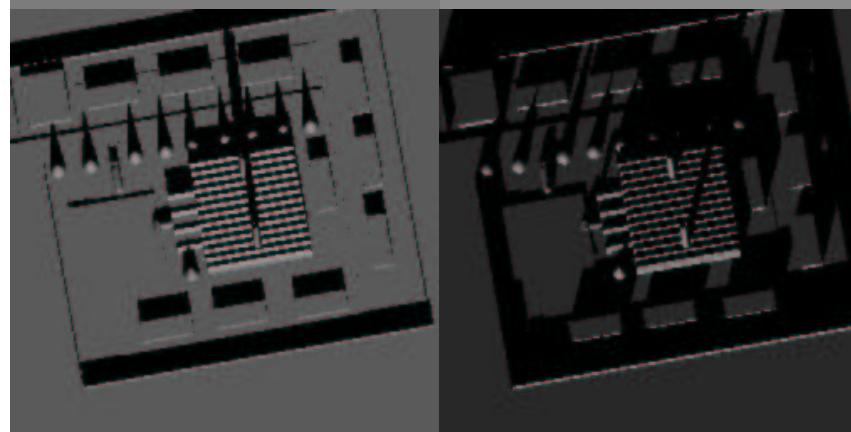
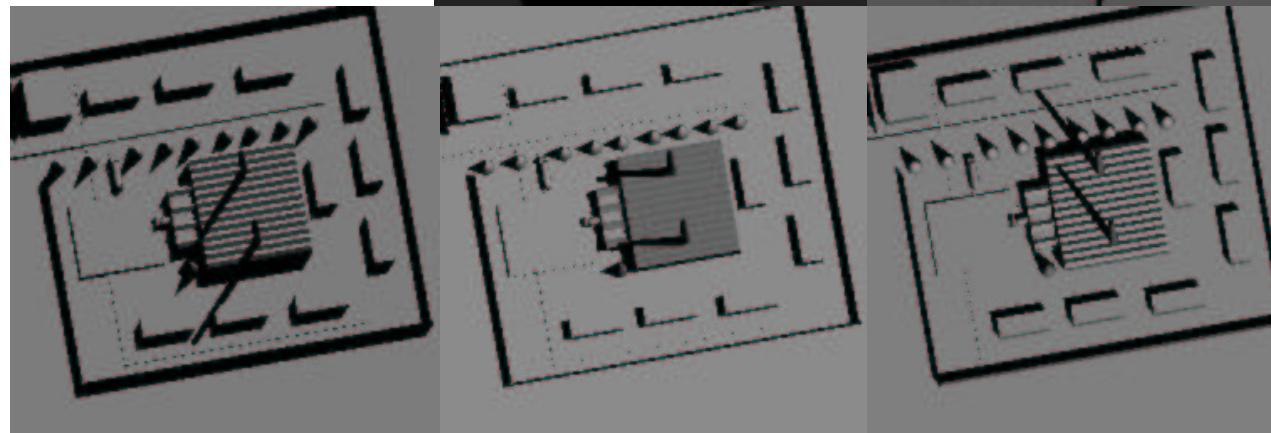
POVRAY Raytraced Scene (www.povray.org)

Shadows History



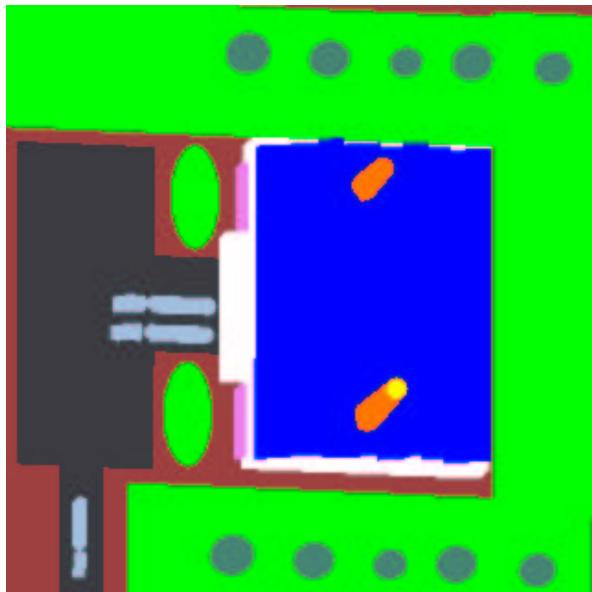
Day from 6 am to 6 pm

July 21 at 34 deg North

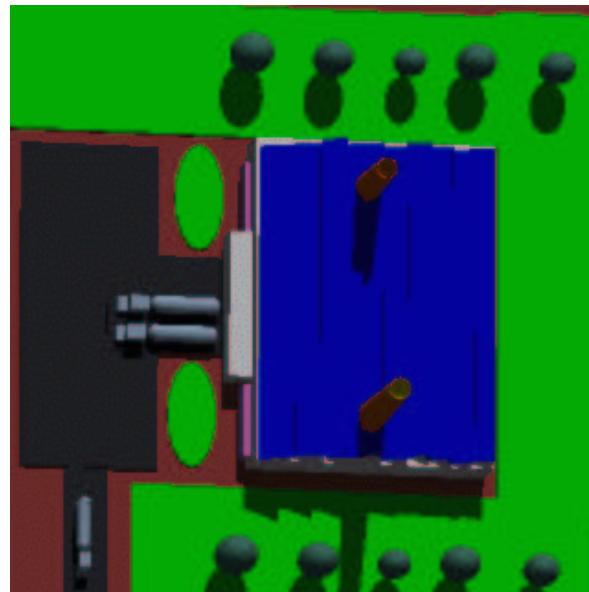


title	6	8
10	12	14
16	18	legend

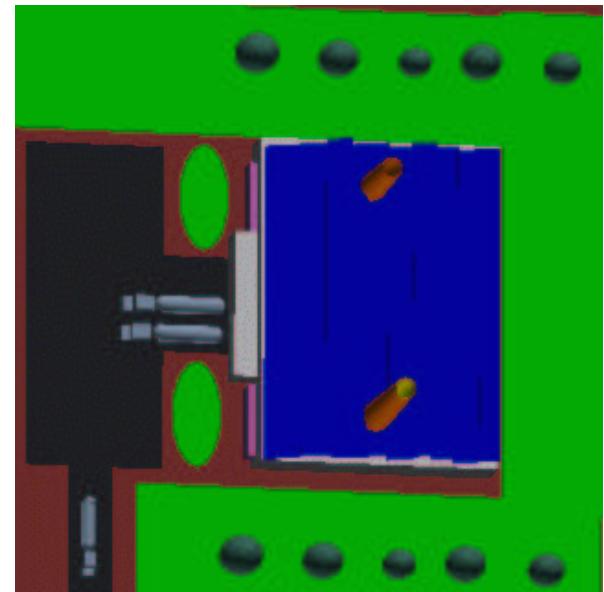
Material, Illumination and Shadow Maps



Material Map $M(x,y)$



$Shade(x,y)$

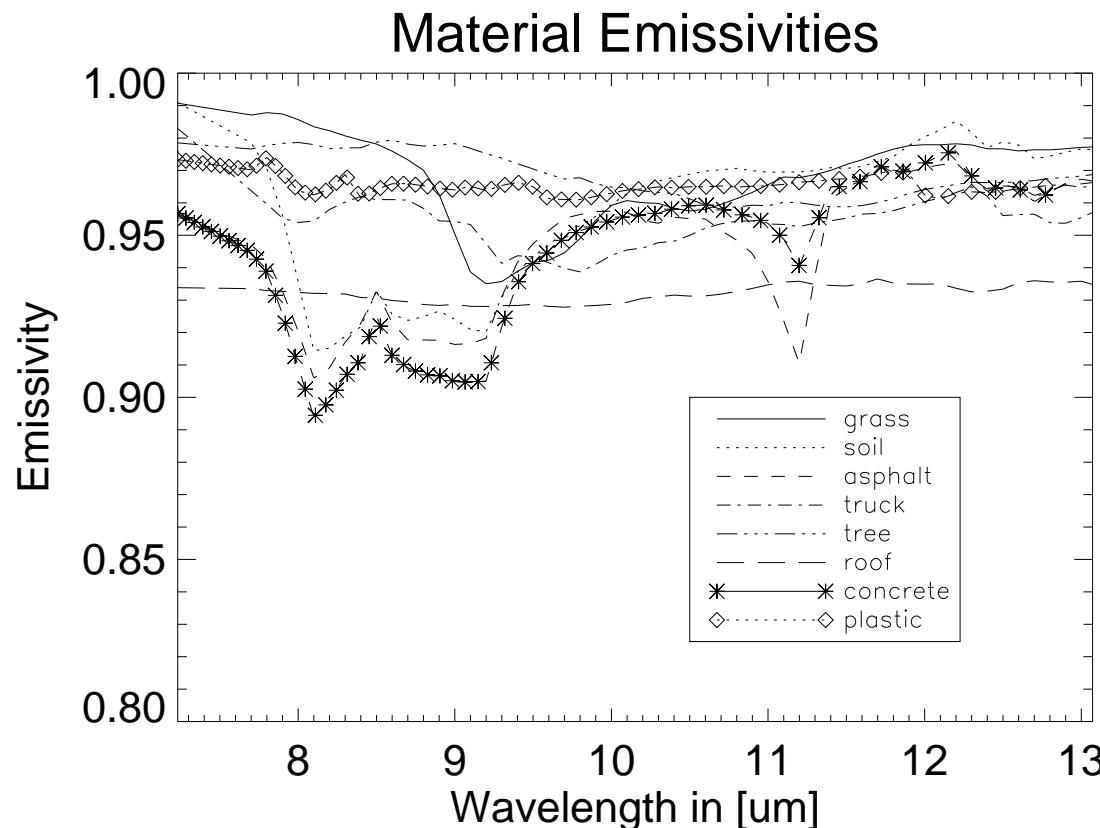


$No_Shade(x,y)$

SPECTRAL MODEL FOR SURFACES

IR Databases:

1. Non-conventional Exploitation Factors Data Systems (NEFDS)
(ciks.cbt.nist.gov/nef/nefhome.html)
2. Salisbury and d'Aria, 1992
(aster.jpl.nasa.gov)



THERMAL MODEL

(a) Statistical Model

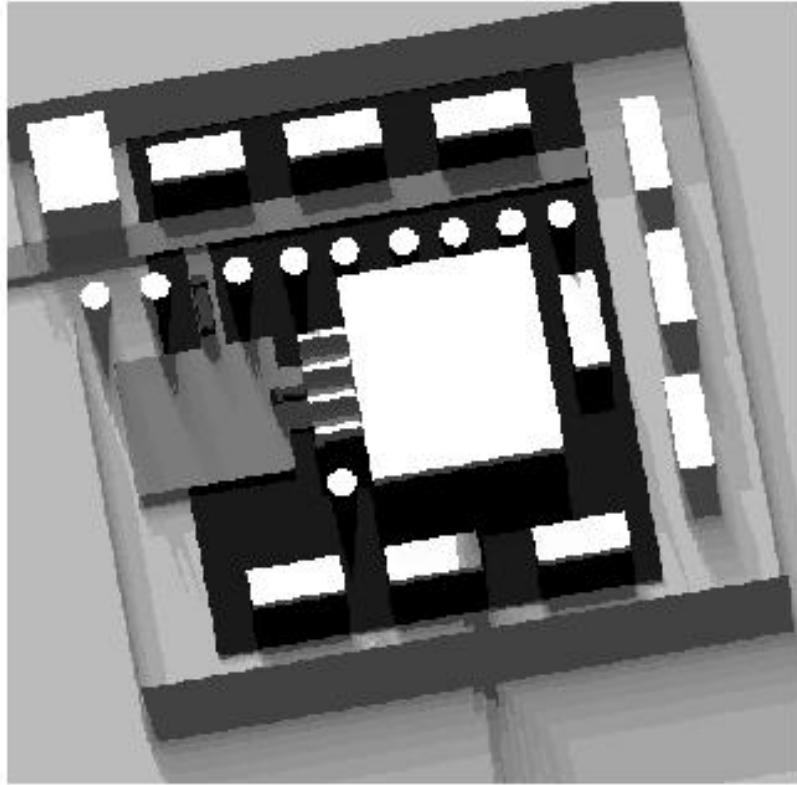
P. Jacobs measured grass, concrete, soil and trees for 3 time periods. Mean temperature and RMS variance are listed for day and night times.

Steps:

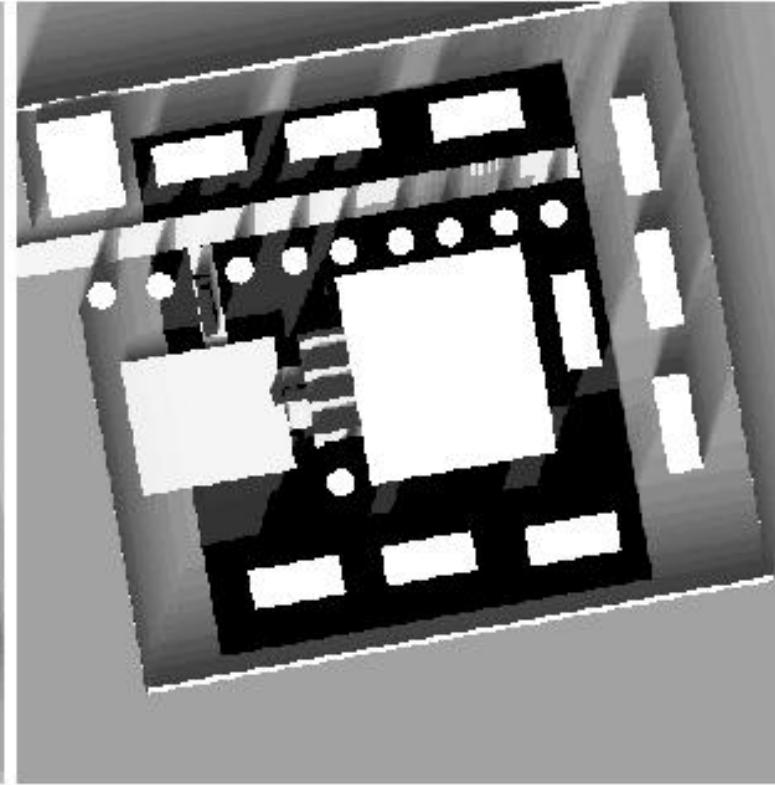
1. Calculate normalize computed diurnal cycles of solar irradiance.
2. Assign each surface a time constant to simulate heat storage.
3. Compute the ground temperature at image coordinates x and y $T_{ground}(x, y, n)$ at time n as:

$$T_{ground}(x, y, n) = A + B \sum_{i=0}^n Shade(x, y, n - i) \exp [-\alpha(M(x, y))(n - i)],$$

where A and B are constants determined to so that the temperature history agrees with the statistically measured temperature range and $\alpha(M(x, y))$ is the material property dependent time constants.



Temperature Map at 8:15 am



Temperature Map at 6:15 pm

Simulated temperatures for the morning (left) and evening (right).

(b) Finite-Difference Model

The energy balance equations states that:

$$q_{rad} + q_{wind} + q_{cond} = E_{storage},$$

where for the n -th time-step:

$$q_{rad,n} = \varepsilon_T \sigma (T_{sky}^4 - T_{0,n}^4) + \varepsilon_V Q_{sol},$$

$$q_{wind,n} = h_{wind} v_{wspeed}^{0.8} (T_{wind} - T_{0,n}),$$

$$q_{cond,n} = k \frac{T_{0,n} - T_{1,n}}{\Delta z}$$

and

$$E_{storage,n+1} = \rho C_p \frac{\Delta z}{2} \frac{T_{0,n+1} - T_{0,n}}{\Delta t}.$$

The temperature of the layer below the surface is given by:

$$T_{1,n} = T_{1,n-1} + \frac{2q_0}{k} \sqrt{\frac{\alpha \Delta t}{\pi}} \exp\left[-\frac{\Delta z^2}{4\alpha \Delta t}\right] - \frac{q_0 \Delta z}{k} \operatorname{erfc}\left(\frac{\Delta z}{\sqrt{4\alpha \Delta t}}\right),$$

where $q_0 = q_{rad} + q_{wind}$, $\sigma = 5.67 \times 10^{-6} W/m^2 K^4$ is the Stefan-Boltzmann constant, h_{wind} is 4.786 for a turbulent flow, v_{wspeed} is the wind speed in m/s, $\alpha = k/(\rho C_p)$ is the thermal diffusivity in m^2/s , $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$ is the complimentary error function, k is the thermal conductivity in $W/(mK)$, ρ is the density in kg/m^3 , C_p is the specific heat in $J/(kgK)$, ε_x is the emissivity in the visible ($x = V$) and thermal ($x = T$), Δt is the time step in s and Δz is the layer thickness in m.

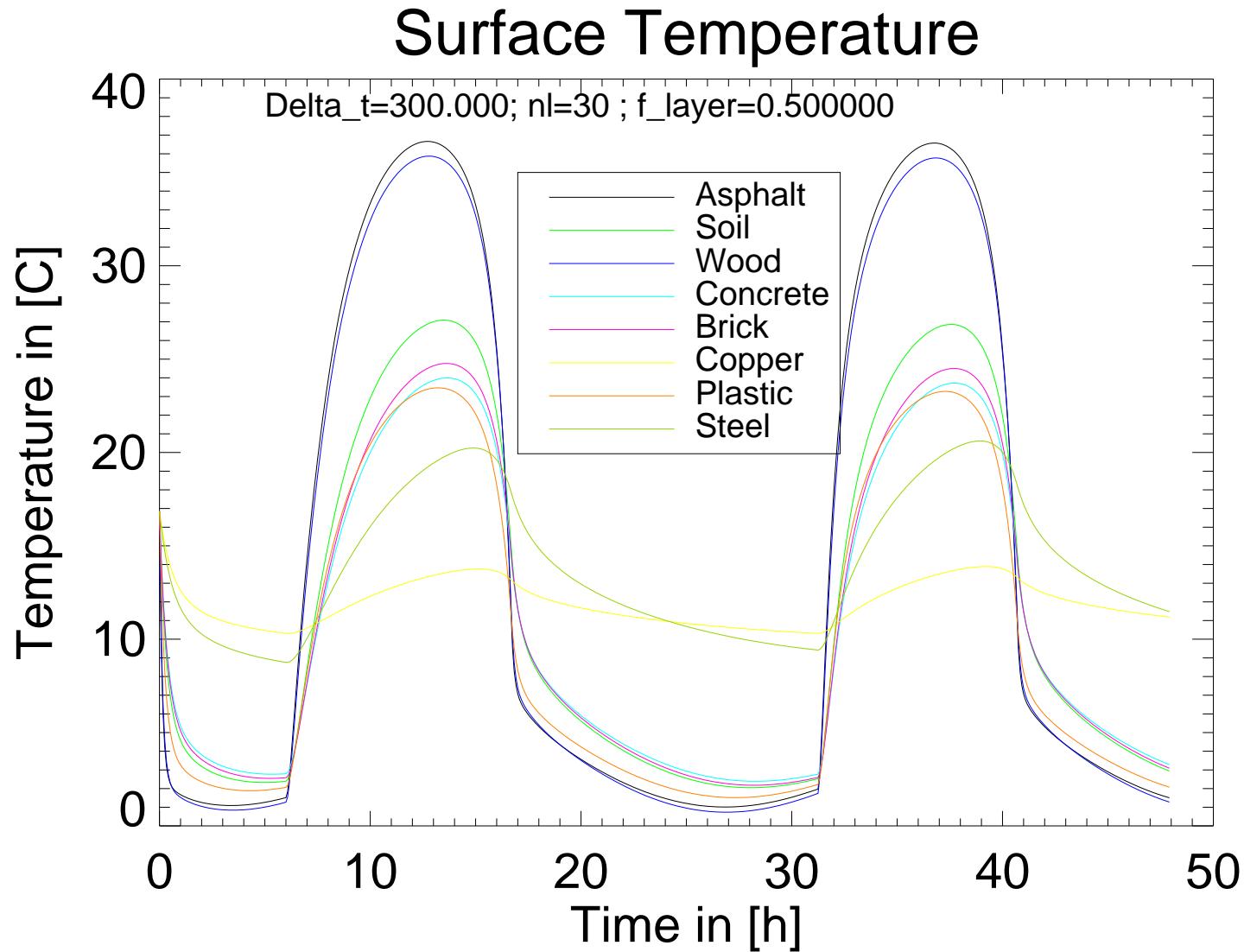
Temperature of surface layer 0:

$$T_{0,n+1} = T_{0,n} + \frac{2\Delta t}{\rho C_p \Delta z} [q_{rad,n} + q_{wind,n} + q_{cond,n}]$$

Typical Thermal and Optical Material Properties

Material	Asphalt	Soil	Wood	Concrete	Brick	Copper	Plastic	Steel
ρ	2115.	1300.	530.	2300.	2000.	8400.	1800.	7920.
k	0.062	0.8368	0.129	1.046	1.0042	230.12	0.2092	13.8
C_p	920.	1046.	2301.	656.9	753.	376.6	1255.	460.2
ε_V	0.83	0.68	0.84	0.60	0.63	0.82	0.52	0.80
ε_T	0.85	0.93	0.94	0.90	0.95	0.33	0.85	0.27

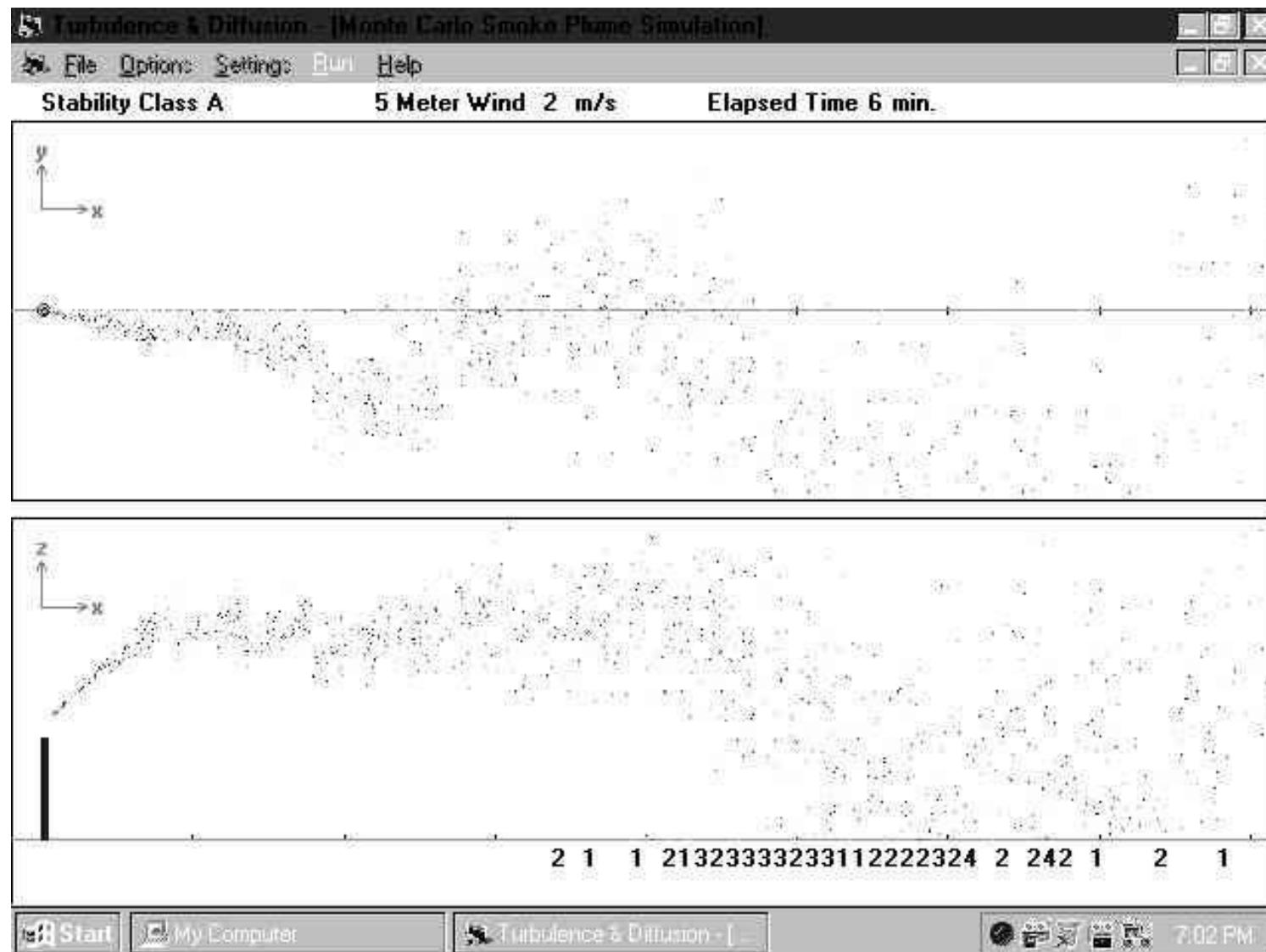
Example: wind speed was 4 m/s, the air temperature 5 deg C, the irradiance was set for Julian day 88 and a latitude of 34 deg



Surface temperatures for two diurnal cycles for eight materials.

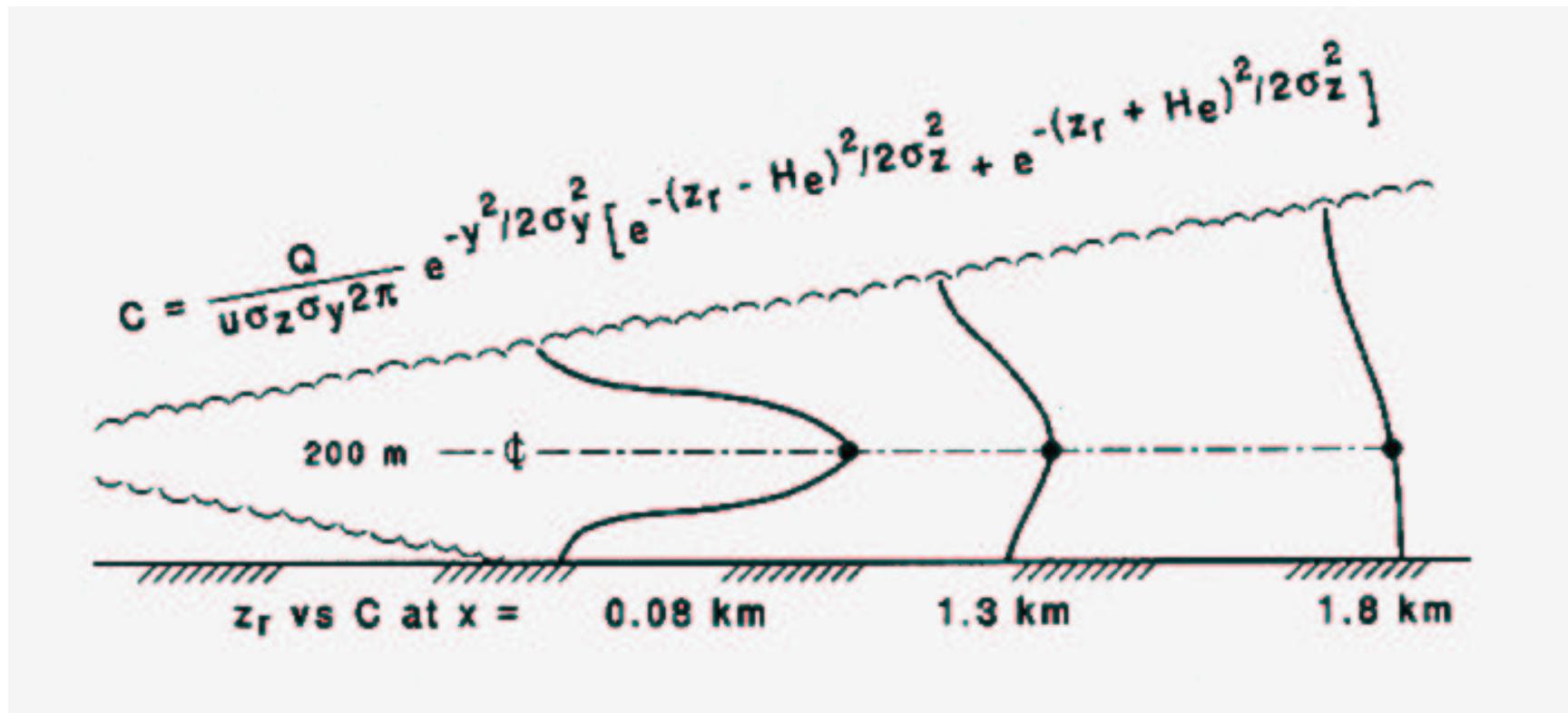
GAS PLUME SIMULATION

(a) Monte Carlo Model by Blackadar, 1997



Disadvantage: Difficult to produce gas concentration maps.

(b) Gaussian Plume Model, e.g. Beychok, 1994

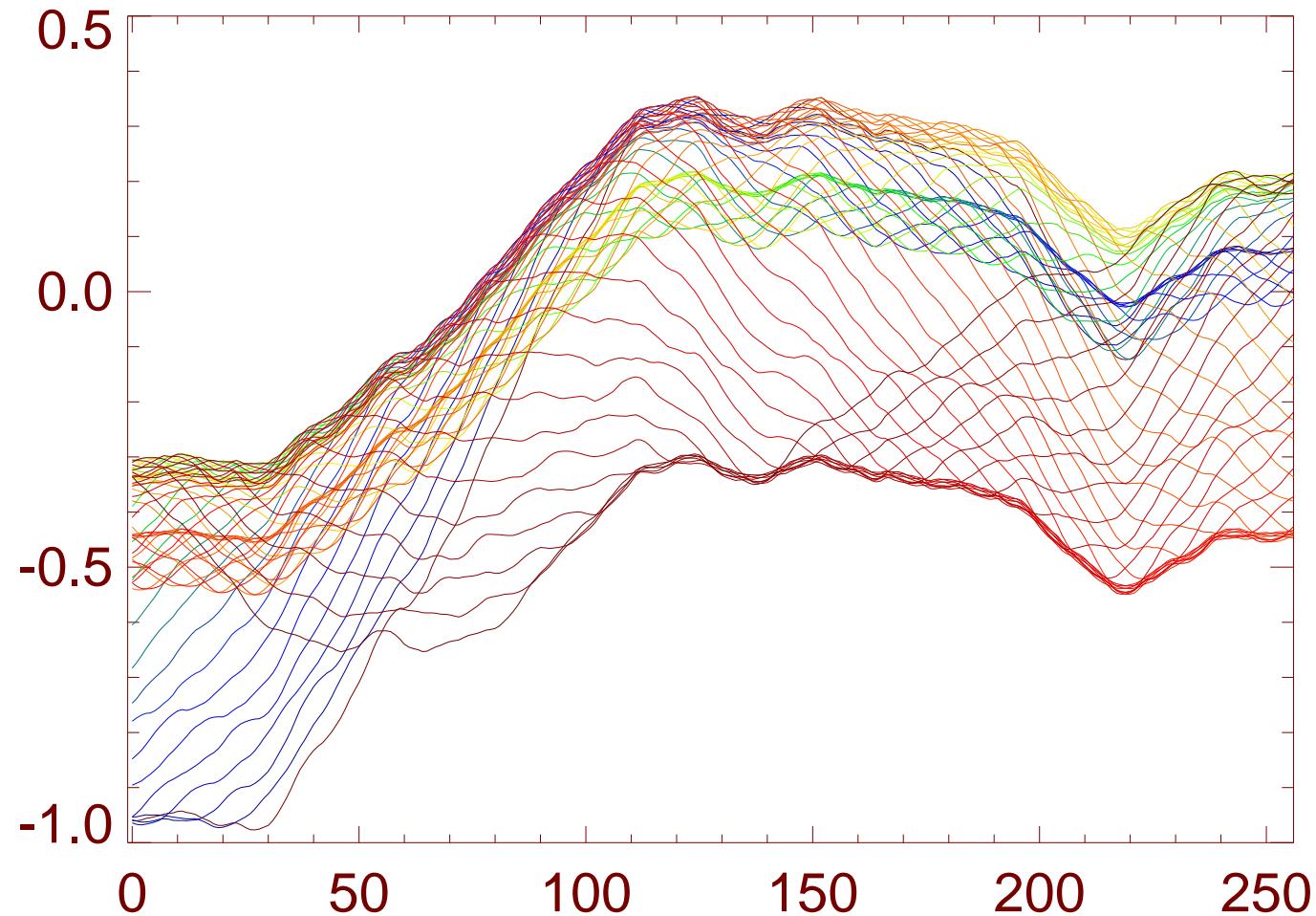


Disadvantage: Represents a long-time average of gas concentration

(c) FRACTAL PLUME GENERATION

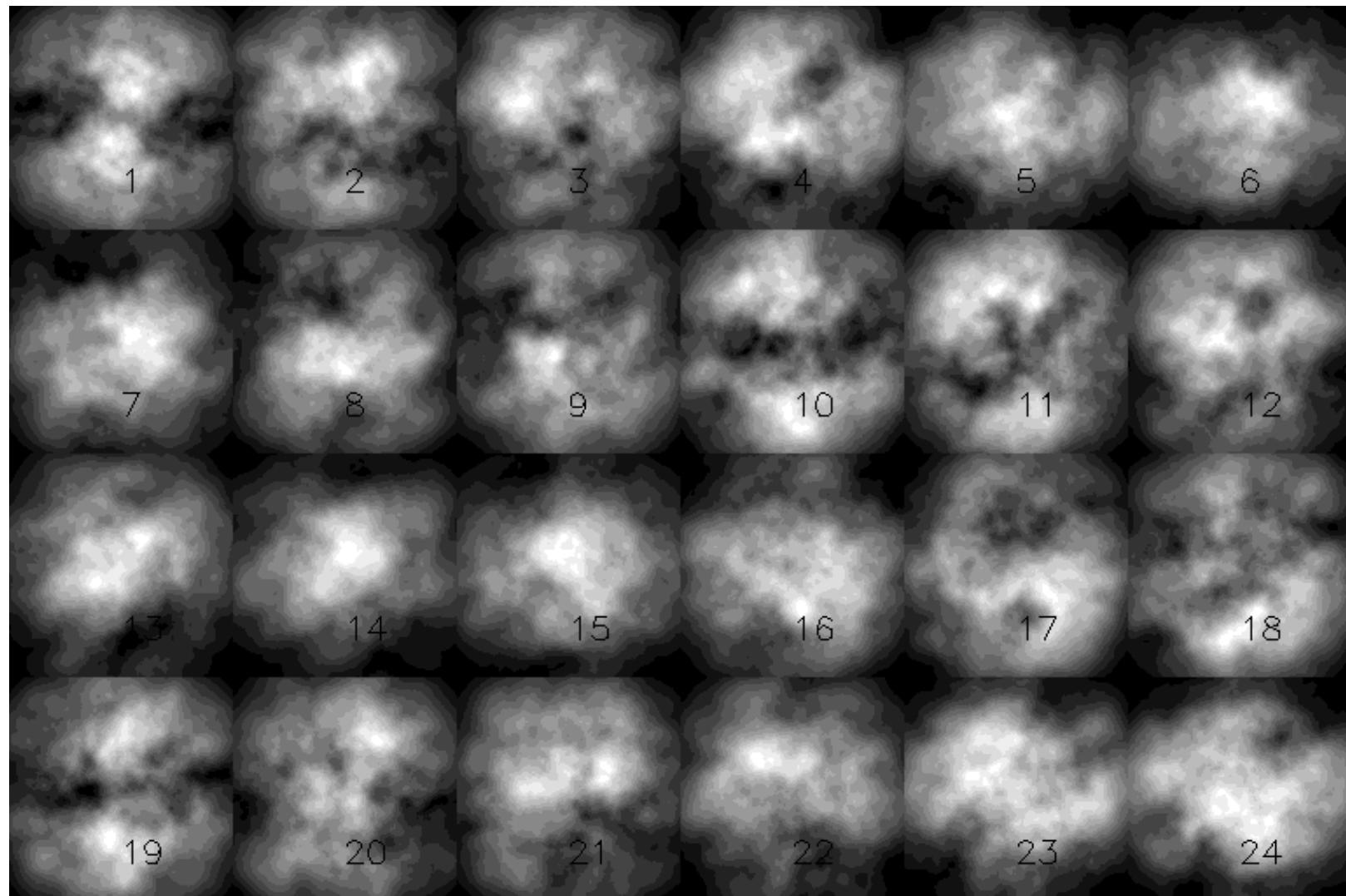
1-D Fractal

Animated 1-D Fractal



Example of a 1-D time-dependent fractal - the curves are shaded according to the time variable

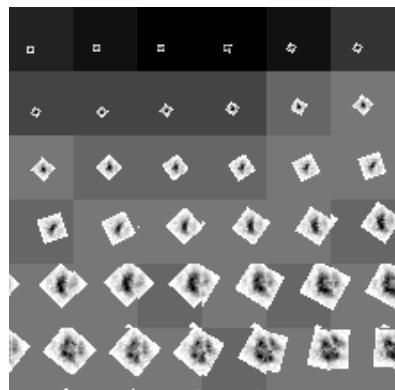
2-D Fractal Generation



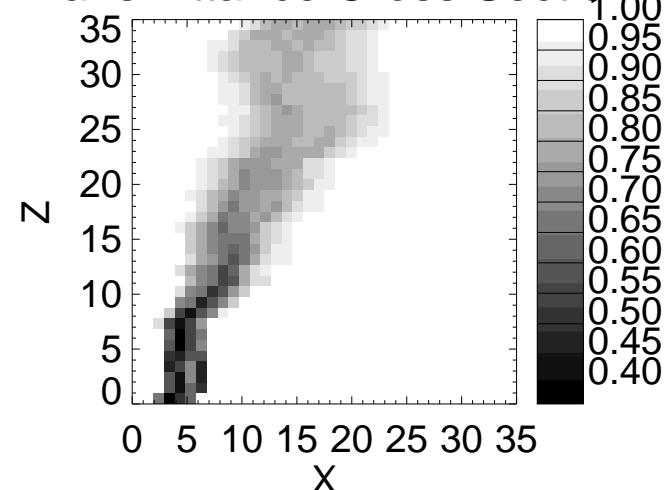
Example of a 2-D time-dependent fractal - the numbers represent time samples

Plume Slices

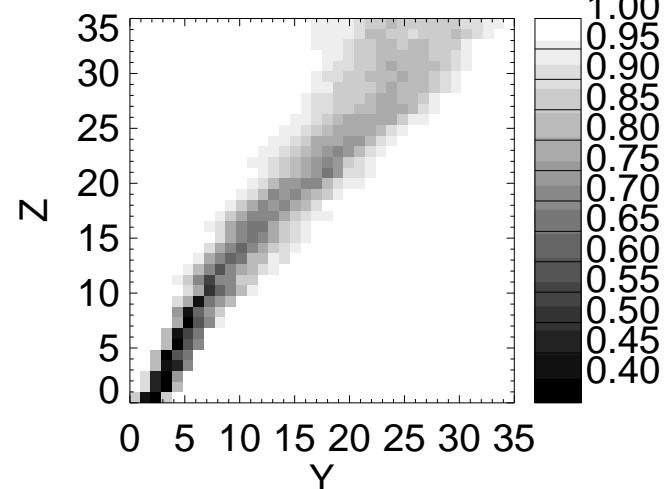
Slices



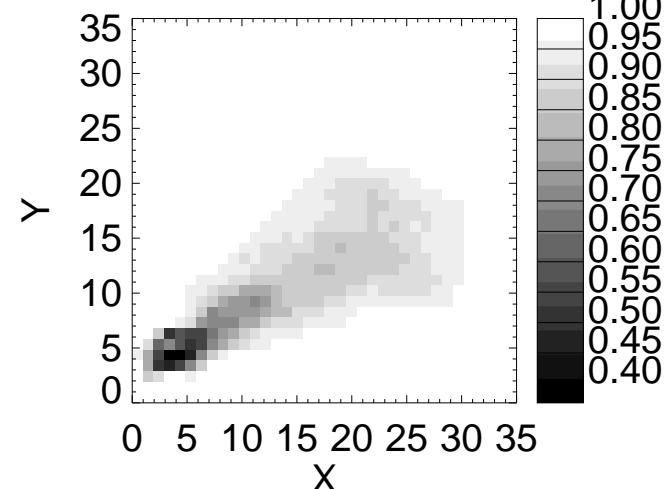
Transmittance Cross Section



Transmittance Cross Section



Transmittance Cross Section

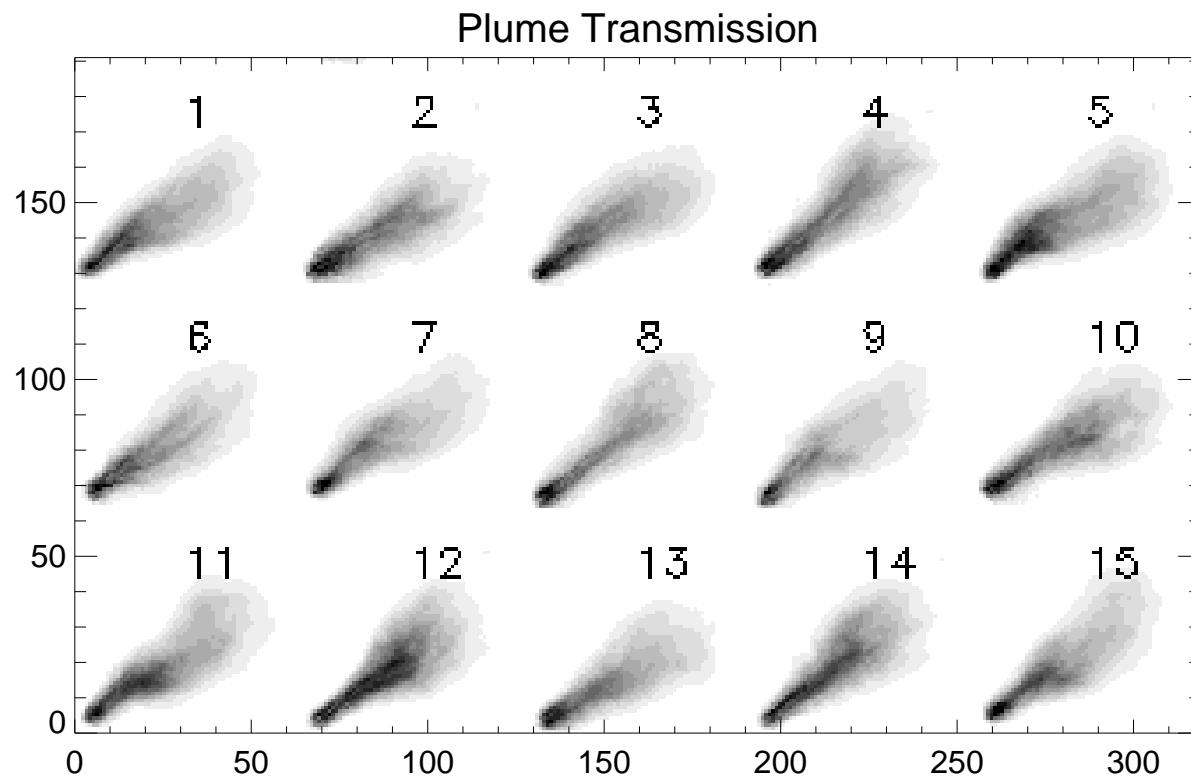


Time sequence of horizontal plume slices demonstrating wind effects, diffusion (scale), plume rotation and changing fractal dimensions (UL).

Plume Temperature Model:

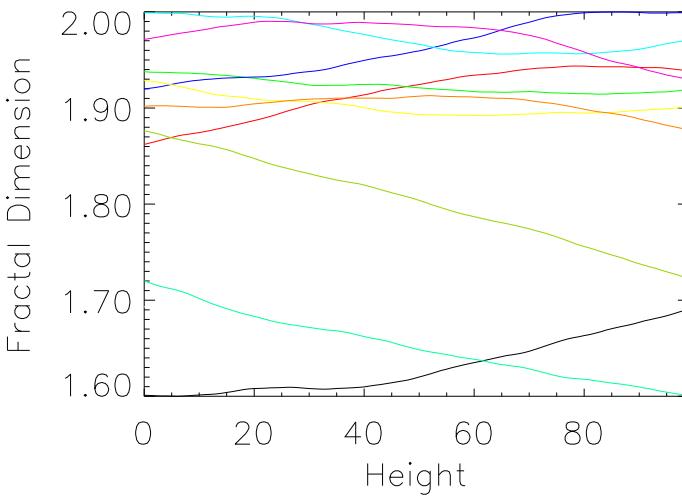
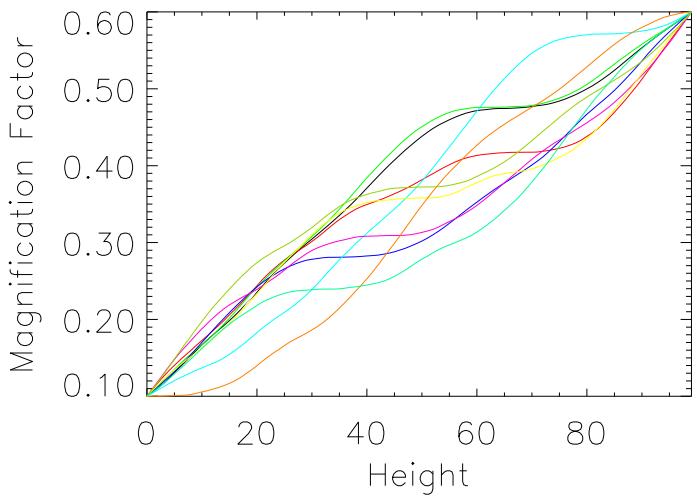
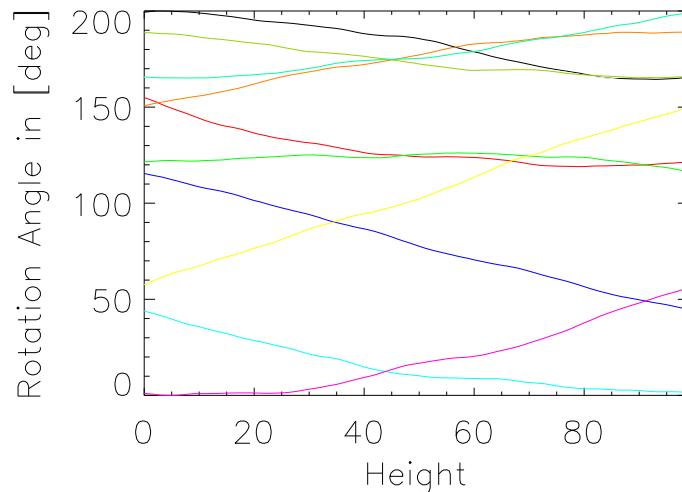
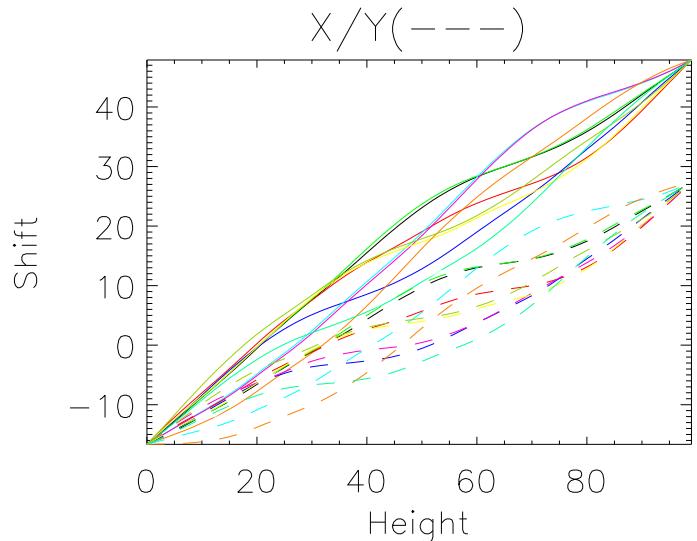
$$T_{gas}(x, y) = T_{air} + \Delta T \frac{1 - \tau_{gas}(\lambda_{absorb})}{\max(1 - \tau_{gas}(\lambda_{absorb}))},$$

where ΔT is a scaling factor, T_{air} is the air temperature and $\tau_{gas}(\lambda_{absorb})$ is the plume transmission at the maximum absorption at wavelength λ_{absorb} of the gas in the spectral range of interest.



Time sequence of plume transmission

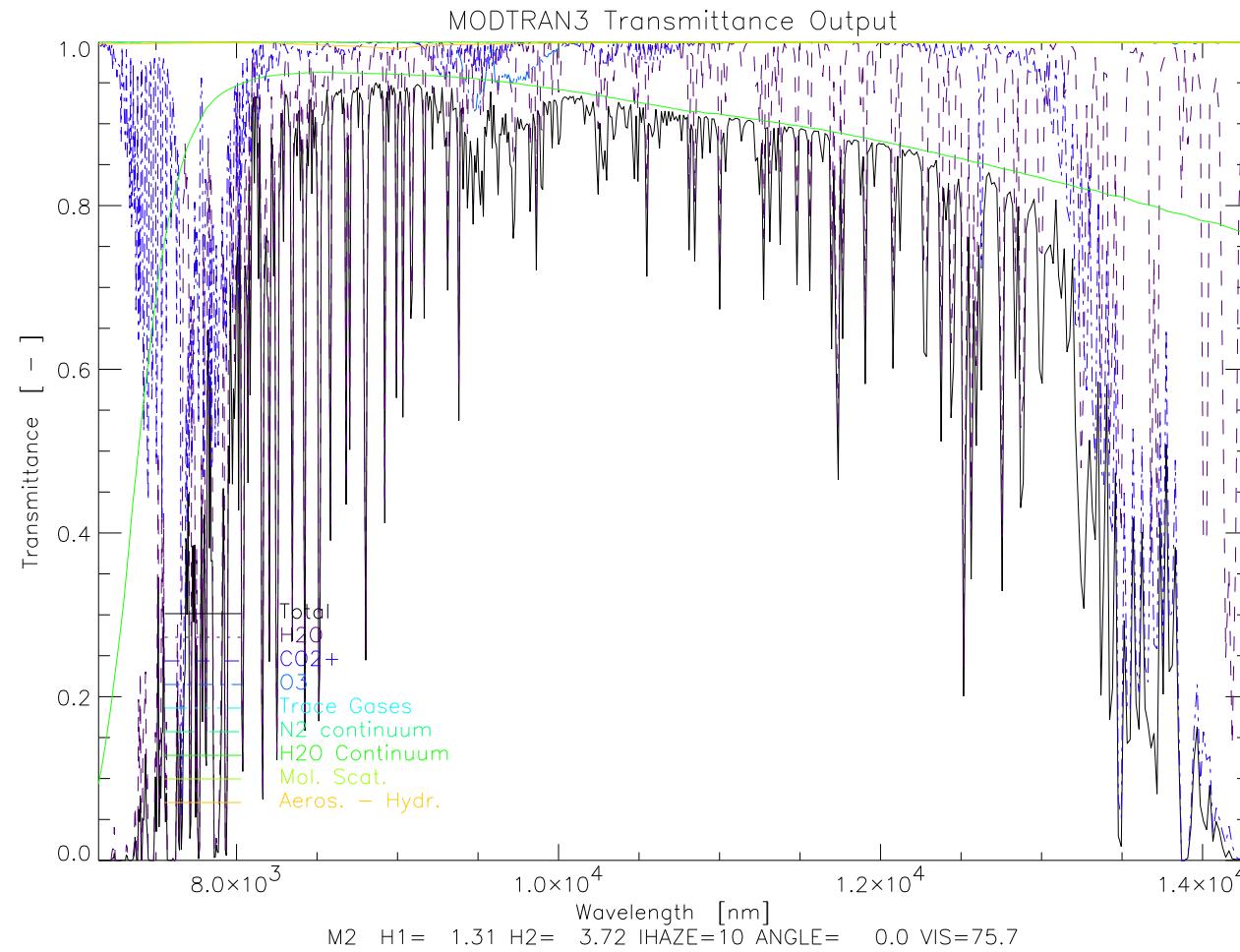
Multi-fractal Plume Variables



Plume variables: x and y shift (UL), rotation angle (UR), magnification (LL) and fractal dimension (LR).

ATMOSPHERIC MODEL

MODTRAN 3 (www.phl.af.mil/VSBM/gpoc/modtran.html)
MODO a GUI ([ftp.geo.unizh.ch/pub/dschlapf/Mod_Util/](ftp://ftp.geo.unizh.ch/pub/dschlapf/Mod_Util/))



Example of a Modtran output showing atmospheric transmission

DATA-CUBE GENERATION

$$L_{total}(x, y, \lambda) = L_{ground}(x, y, \lambda) + L_{gas}(x, y, \lambda) + L_{path\uparrow}(\lambda) + L_{reflected}(x, y, \lambda),$$

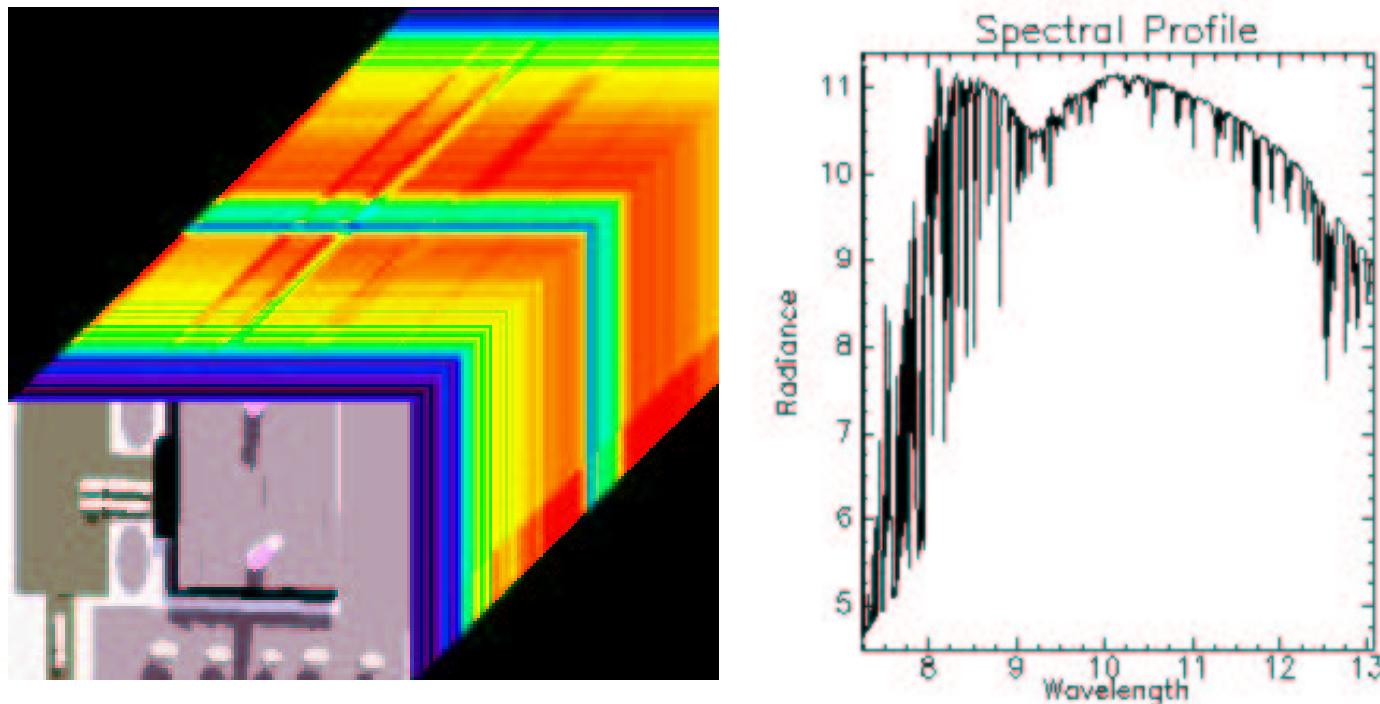
where

$$L_{ground}(x, y, \lambda) = \varepsilon(x, y, \lambda)B(\lambda, T_{ground}(x, y))\tau_{gas}(x, y, \lambda)\tau_{atmo}(\lambda),$$

$$L_{gas}(x, y, \lambda) = [1 - \tau_{gas}(x, y, \lambda)]B(\lambda, T_{gas})\tau_{atmo}(\lambda),$$

$$L_{reflected}(x, y, \lambda) = L_{path\downarrow}(\lambda)[1 - \varepsilon(x, y, \lambda)]\tau_{gas}(x, y, \lambda)\tau_{atmo}(\lambda),$$

and $B(\lambda, T)$ is the Planck function describing the spectral radiance in $[W/(cm^2 \text{ ster } \mu m)]$.



Simulated thermal hypercube with sample spectrum.

GAS SPECTRAL LIBRARIES

EPA's Emission Measurement Center

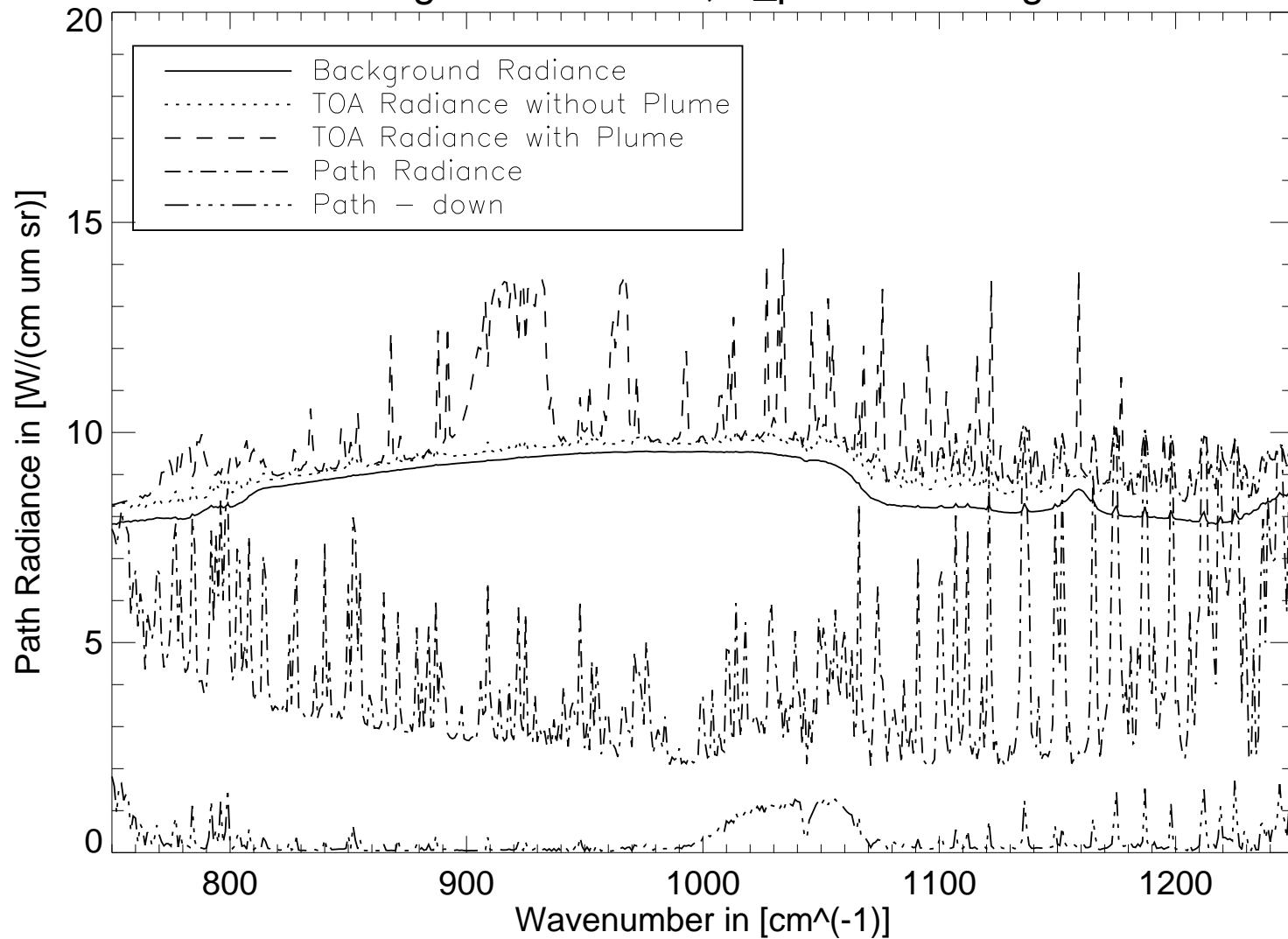
(134.67.104.12/html/emticwww/ftir.htm)

- 1 cm^{-1} resolution
- 403 measurements of about 180 different gases
- Free-path length measurements of gases at several temperatures

Galactic Industries Web site (www.galactic.com)

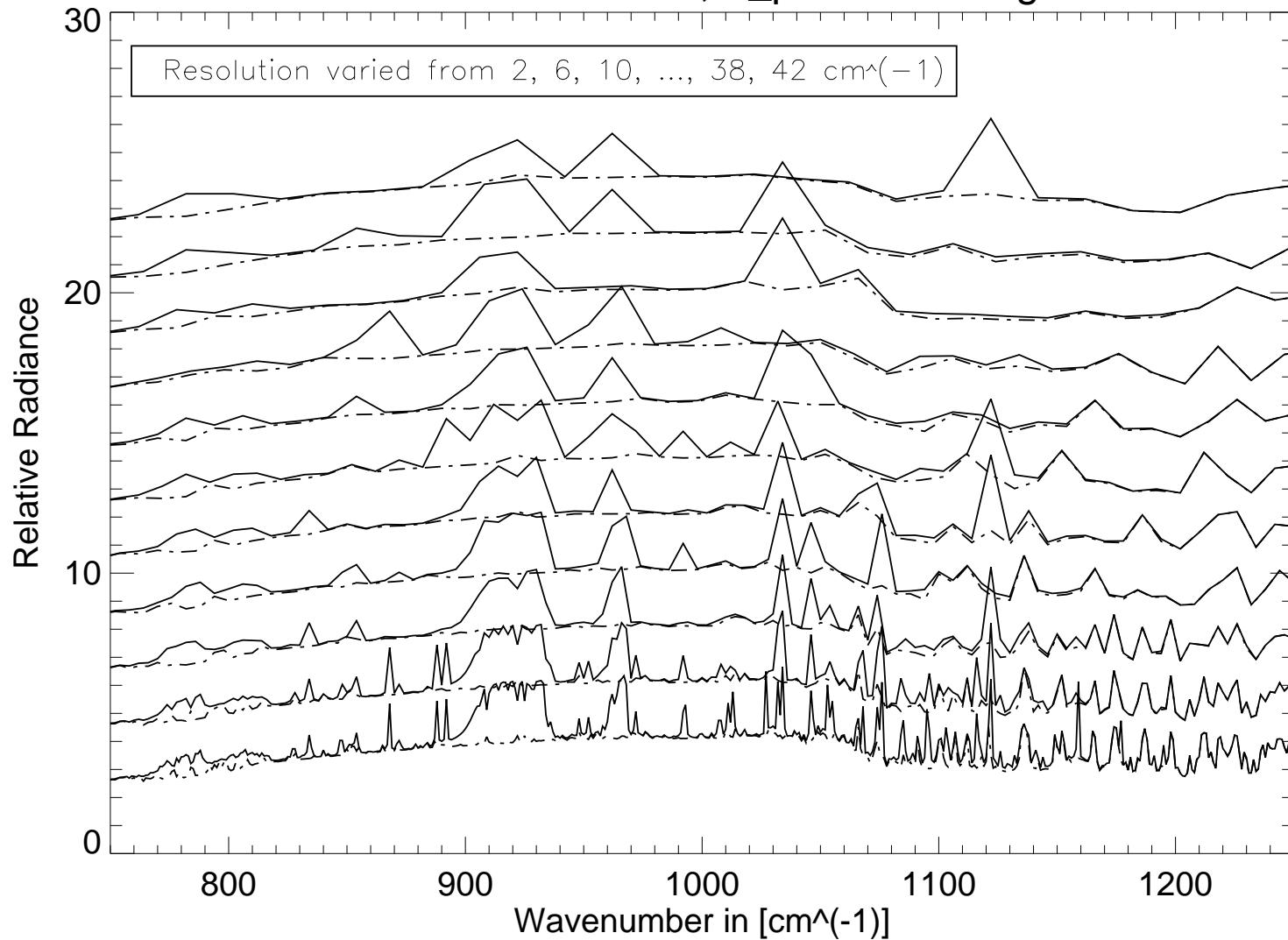
- EPA FT-IR Vapor Phase Library (3276 gases at 4 cm^{-1} sampling)
- David Sullivan FT-IR Library
- ...

Background: Quartz ; T_plume=60 deg C



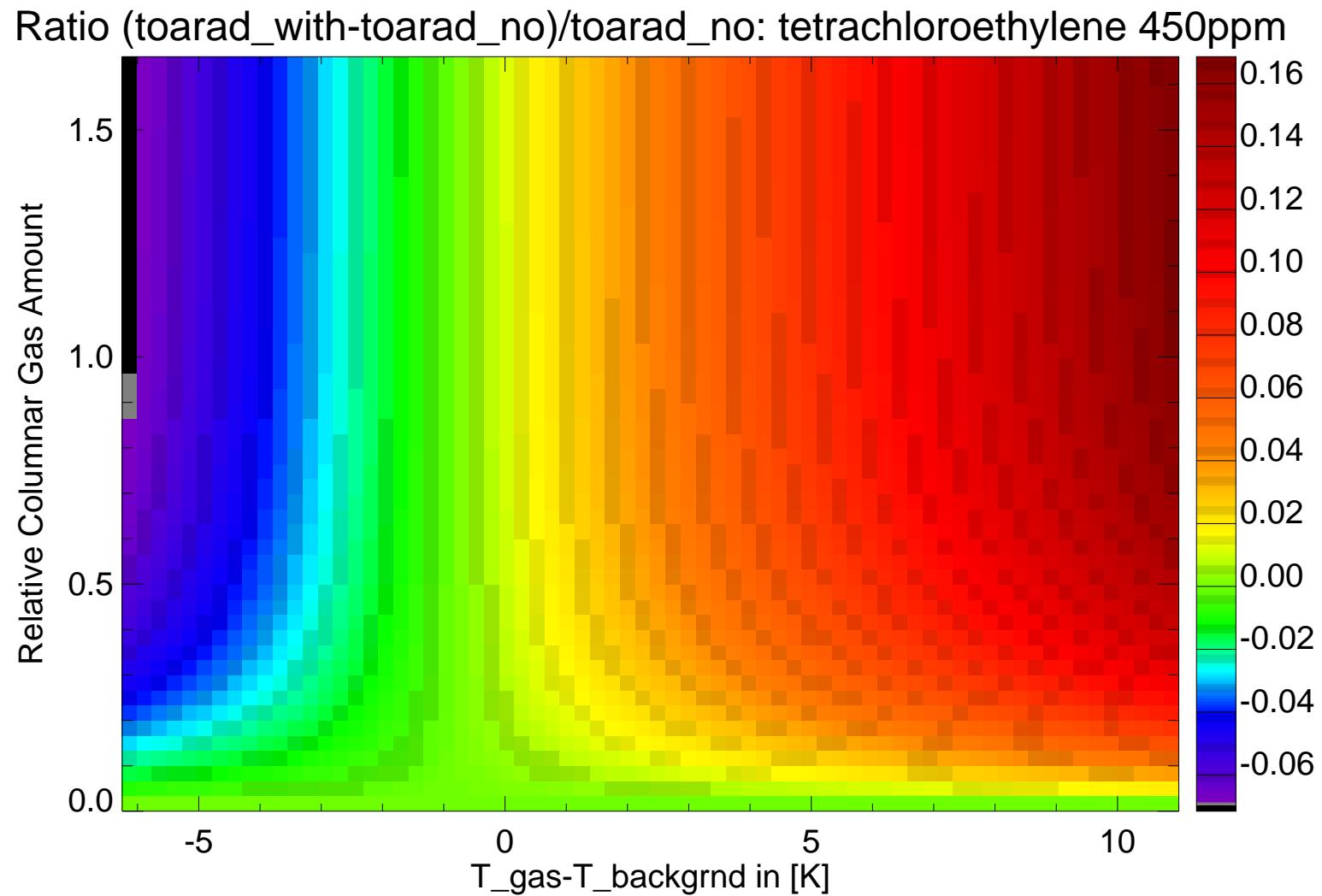
Mixture of 60 deg C gases (500 ppm Ammonia and 450 ppm tetrachloroethylene)
radiances computed over quartz surface at 32 deg C.

Effect of Resolution ; T_plume=45 deg C



The effect of spectral resolution on the on-plume (solid line) and off-plume (dashed line) radiance.

Effect of temperature difference between background and plume



$(On - Plume - Off - plume)/(Off - Plume)$ ratio for TCE

Temperature-Emissivity Separation (TES) Algorithm

Steps:

1. Compute the initial ($n = 0$) blackbody temperature $T_{bb,n}$ in an atmospheric window from an atmospherically corrected radiance $L_{cor,0}$:

$$T_{bb,n} = B^{-1}(\lambda_{window}, L_{cor,n})$$

with

$$L_{cor,n} = \frac{L_{total} - L_{path\uparrow}(CW, T_{atmo}) - L_{path\downarrow}\varepsilon(n)}{\varepsilon(n)\tau_{atmo}(CW)},$$

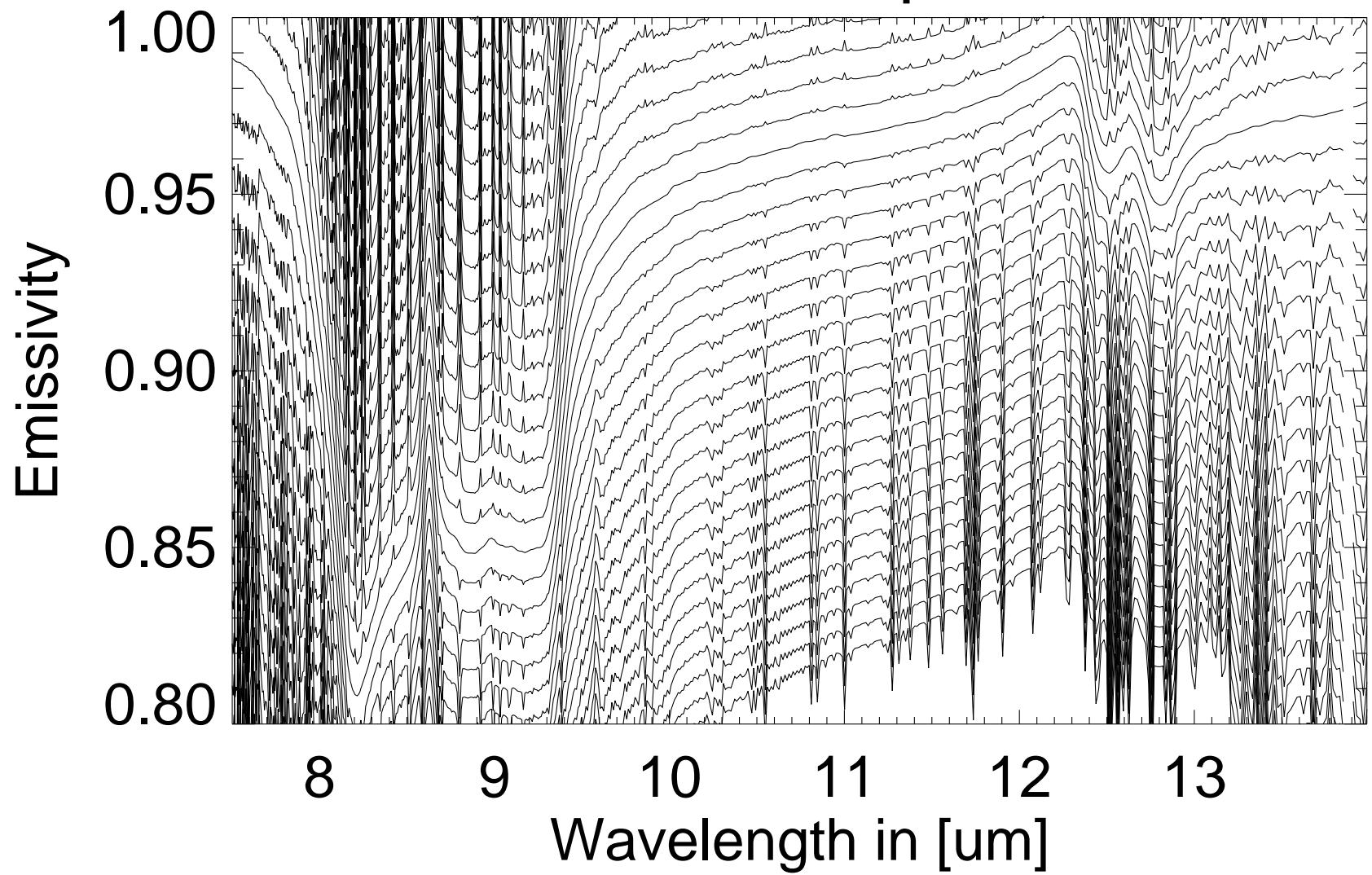
where CW stands for column water, T_{atmo} is the effective atmospheric temperature and $\varepsilon(0) = 0.95$.

2. Compute spectral emissivity: $\varepsilon(n) = L_{cor,n}/B(\lambda, T_{bb,n})$, $n = 1, 2, \dots$
3. Vary the surface temperatures $T_{bb,n} = T_{bb,0} + i\Delta T$, $i = 1, 2, \dots$, change the columnar water amounts and the effective atmospheric temperatures and recompute $\varepsilon(n)$ iteratively using steps 1-3.
4. Stop iteration when emissivity is smoothest, i.e. when

$$\sigma(\varepsilon(n)) = STDEV \left[\varepsilon_i(n) - \frac{1}{K} \sum_{j=i-K/2}^{i+K/2-1} \varepsilon_j(n) \right]_{i=K/2+1, \dots, M-K/2} = Min,$$

where the spectrum consists of M channels.

Iterations to find Temperature Offset



Retrieved emissivity as a function of temperature offset δT

Conclusions

Hyperspectral cubes simulation includes:

- Realistic temperature distributions,
- Material dependent emissivities,
- Complex time-variant gas plumes, and
- Atmospheric absorption and emission.

Temperature-Emissivity Separation

- Study effects of spectral/spatial resolution, calibrations, SNR

Future Work

- Include detailed sensor simulation,
- Add hyperspectral textures,
- Handle mixed pixels, and
- Perform detailed TES analysis for various sensors.